

Analysis and Design of Integrated Magnetorquer Coils for Attitude Control of Nanosatellites

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Abstract—The nanosatellites typically use either magnetic rods or coil to generate magnetic moment which consequently interacts with the earth magnetic field to generate torque. In this research, we present a novel design which integrates printed embedded coils, compact coils and magnetic rods in a single package which is also compliant with 1U CubeSat. These options provide maximum flexibility, redundancy and scalability in the design. The printed coils consume no extra space because the copper traces are printed in the internal layers of the printed circuit board (PCB). Moreover, they can be made reconfigurable by printing them into certain layers of the PCB, allowing the user to select any combination of series and parallel coils for optimized design. The compact coil is wound around the available space in a 1U compliant CubeSat panel and it can accommodate much more number of turns compared to printed coil; consequently generating more torque. The magnetic rod is made compliant with the existing available options and can easily be integrated in the panel. This design gives a lot of flexibility because one can choose to optimize power, optimized torque or rotation time by choosing among the available magnetorquer options. The proposed design approach occupies very low space, consume low power and is cost effective.

The analysis in terms of generated torque with certain applied voltages, trace widths. The analysis results in terms of selection of optimized parameters including torque to power ratio will be presented.

Keywords—ADCS; Magnetorquer; Reconfigurable; Printed; Compact; Optimum; magnetorquer Rod; Nanosatellite;

I. INTRODUCTION

With the passage of time, the size of the satellites is reducing and their applications are increasing. Due to their low price, mass and size, it has become more attractive for universities, small research organizations and space agencies to build, test and launch their own satellites. With the reduction of size of the CubeSats and nanosatellites, the designing and placement of all the subsystem in a reduced space has also

become a challenge. In order to stabilize the tumbling satellite, the attitude control system is very necessary. There are two types of attitude control systems i.e. passive and active [1-6]. The permanent magnetics and the gravity gradients are passive type. They being cost effective, consume no power but no pointing accuracy is achieved using these types of actuators. The majority of the missions these days require better pointing accuracies. The active control systems are typically used for in missions where better pointing accuracy is desired. The magnetorquer is a good option to control the attitude of nanosatellite. They use the local (earth) magnetic field to generate the torque, which is used to rotate the satellite.

In this work, we present a combined design of attitude control system by combining different types of magnetorquers to overcome the main constraints like available power, cost, mass and space availability. The printed or embedded coil, compact coil and cylindrical rod are combined in a CubeSat compliant panel to achieve three axis control. The detailed analysis has also been performed for all the types and the proposed design is also compared with the commercial designs. The thermal analysis has also been presented for the proposed design.

The ACS manages the satellite orientation, in order to point its antennas toward ground station or solar panels towards the sun. For this purpose normally permanent magnets, reaction wheels and magnetic rods are used. Permanent magnets are cheap, simple, light and consuming no power. But they have inadequate pointing accuracy and give very little choices on the pointing direction. Reaction wheels and magnetic rods have better pointing accuracy and can orientate satellite in any direction but their price, weight and size make them incompatible with CubeSats standard Nanosatellites like AraMiS-C1.

The best solution to this problem is the design of reconfigurable magnetorquers which are able to produce required magnetic moment and consequent torque for any desired spacecraft configuration.

The design having printed magnetorquers, compact magnetorquers and magnetic rods has been accomplished for iCube and AraMiS satellites [8-9]. The design approach is based on smart panels which can be integrated together to form any CubeSat configuration [8-9]. A panel showing printed magnetorquer in the internal layers is shown in Fig.1.

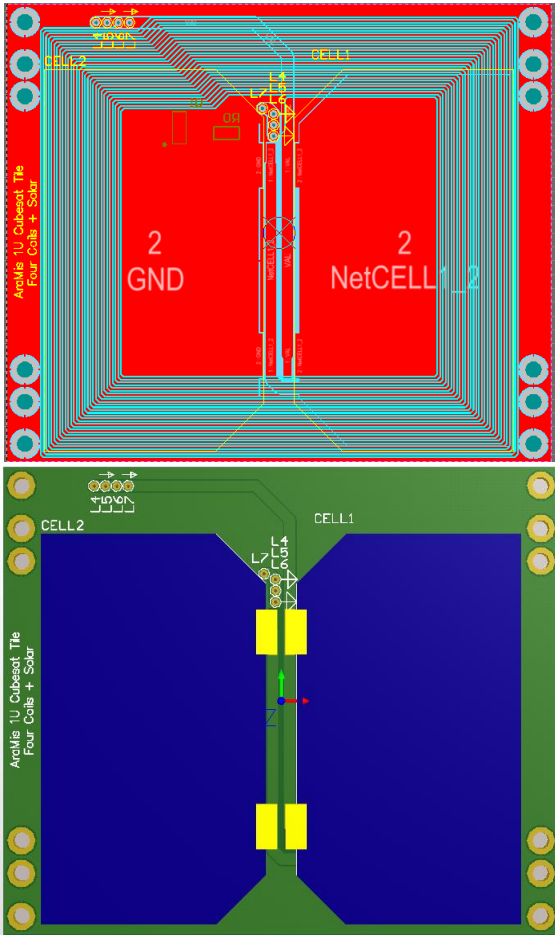


Fig.1 Design of printed coil on a CubeSat panel

The printed Magnetorquer is a better choice for attitude control and stabilization of Nanosatellites when the mission requires less torque and less power consumption. The compact magnetorquer is suitable for better pointing where consuming more power to generate more torque. The cylindrical solution provides best pointing but it needs more area, power to generated torque.

The goal of this work is to provide CubeSats with reconfigurable option of using all the possible magnetorquers keeping power, torque, and torque to power optimized [7].

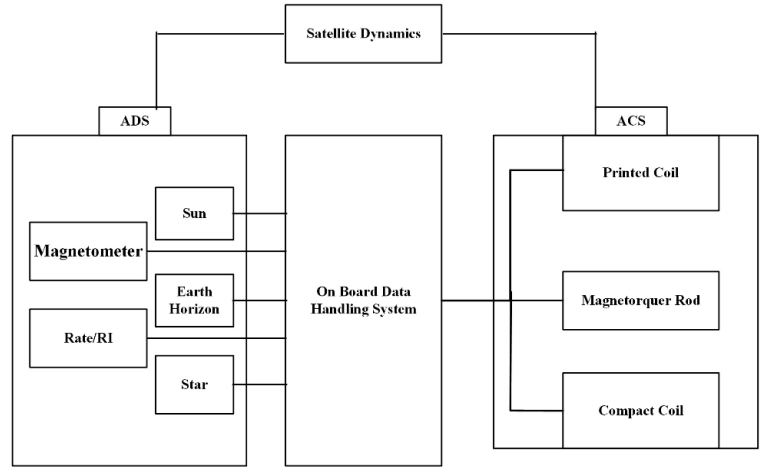


Fig.2 Flow diagram of the system

A completed flow diagram of the system is shown in Fig. 2. The attitude of the spacecraft is determined with the help of certain attitude sensors and this attitude information is sent to on board data handling system (OBDH) with the current and target attitude. The OBDH sends torque commands to actuate either compact, printed or magnetic rod after calculations of desired torque for desired attitude attainment. The new attitude is fed back to the onboard computer and the loop repeats.

This work suggests an optimized combined design where these attitude control solution are used by optimizing certain parameters like trace widths, applied voltages, to generate torques while keeping torque to power ratio optimized. The theoretical design has been verified by experimental setup.

II. MGENETORQUER DESIGN

A. Printed Magnetorquer

The printed magnetorquer design is selected by performing the theoretical calculations on generated torque, torque to power ratios for CubeSat complaint panels by changing the applied voltage. The designed printed magnetorquer is fully compliant with the CubeSat dimension and requires no extra space since the traces are embedded in the internal layers of the board. The board has been designed using optimal parameters including the selection of outer and inner copper dimensions, trace widths, distance between two adjacent traces and power consumption analysis vs the generated torque. The copper traces of magnetorquer coil are printed into the inner layer of printed circuit board (PCB). The selected dimensions of the printed magnetorquer are shown in Fig.3.

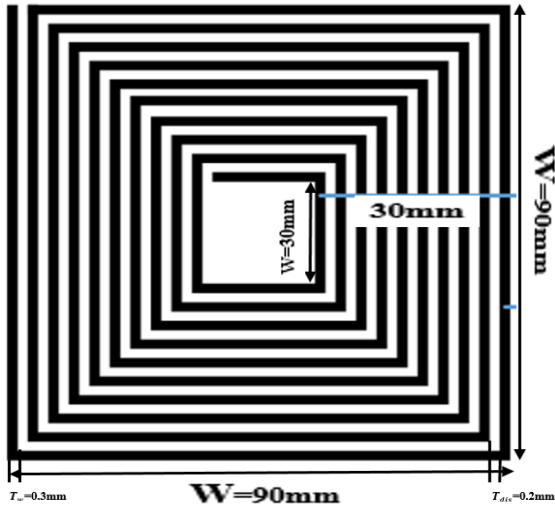


Fig.3 Dimensions of printed coil

After the analysis part, the optimum placement of printed coil on a 1U complainant panel is performed. Each coil trace has a width of 0.5 mm and thickness of 18 μm . Each turn is approximated like square, separated by 0.2 mm distance and has four sides. For our panel design which can be integrated into CubeSat dimensions, the single coil has a bundle of 42 turns in a single Printed Circuit Board layer and has a bundle width of 30 mm with outer dimensions being 90 mm \times 90 mm and inner dimensions being 30 mm \times 30 mm.

The cross sectional trace area (width and thickness), length and number of turns of coil affect the resistance of the magnetorquer coil which is related to the parameters like torque, power and heat generated for target maneuver. The key parameters related to the design are discussed in the coming sections. The design parameters of embedded magnetorquer coil are shown in table 1.

Table 1

Embedded magnetorquer coil parameters of single layer

Parameter	Values
Single turn average length	240 mm
Length of single coil	10,080 mm
Outer-most turn side	90mm
Inner-most turn side	30mm
Trace thickness	1.8 μm
Trace Width	0.5 mm
Area occupied by turns(1 layer)	0.1671 m ²
Distance between two adjacent traces	0.2 mm
Copper resistivity	1.7*10 ⁻⁸
Nominal Magnetic moment(by 1 layer)	0.0284 Am ²
Working voltage	2V to 7V

The optimization of our design is based on applied voltage, generated torque and T/P Ratio. It is apparent from the graphs of Fig.4 that the torque to power ratio is decreasing by increasing the turn width therefore we conclude that; the smaller the turn width, the greater the torque to power ratio.

By increasing turn width, the torque increase but at the expense of temperature rise as evident from the Fig.4.

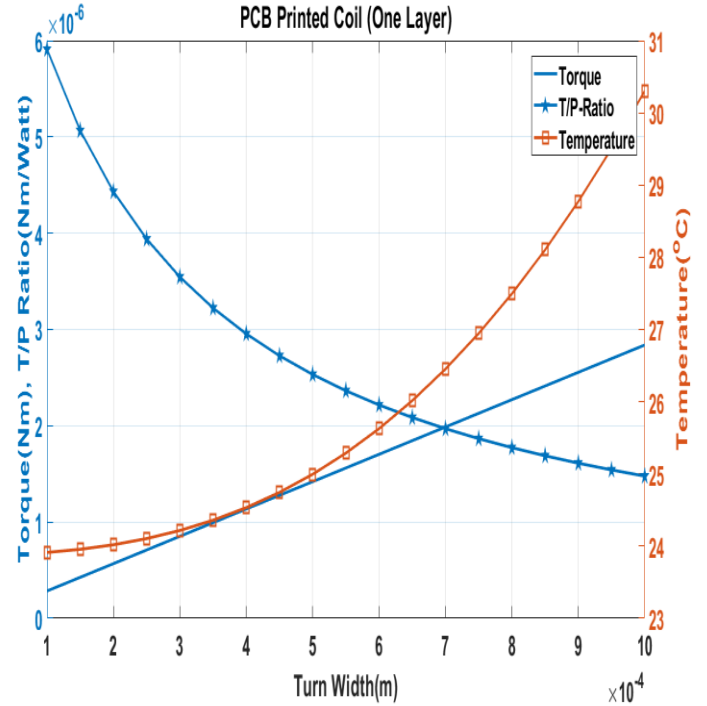


Fig. 4 Turn width Vs Torque, τ /P, Power and current for printed magnetorquer

The relation between applied voltage and torque, torque to power ratio and temperature of the coil at specified turn width, external and internal side length is shown in Fig.5. By increasing the applied voltage, the generated torque and temperature is increasing due to large consumption of power at higher voltages. The torque to power ratio is decreasing as the applied voltage is increasing as shown in Fig.5. The analysis suggests that better torque to the power ratio is achieved at lower working voltages

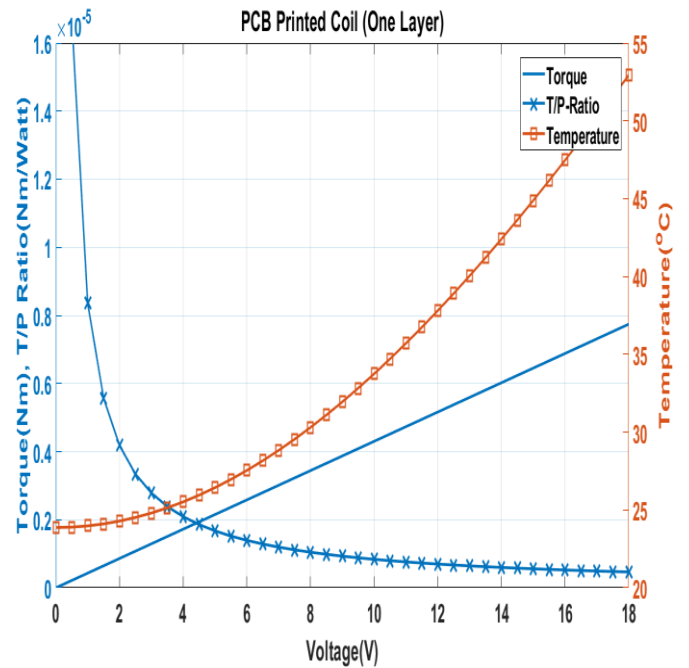


Fig.5 Voltage Vs Torque, τ /P and temperature for printed magnetorquer

B. Compact Magnetorquer

The compact magnetorquer coil is wound on the surface of the panel printed circuit board for generation of better torque with the applied voltage. The laminated copper wire is wound around the panel such that the coils are held on the top of the surface. The external most dimension of winding structure is 90mm \times 90mm and the height of coil is 5mm for turns of specified gauge of wire. The analysis has been performed for variable wire gauges (AWG 26-33). The cross sectional view of the compact magnetorquer is shown in Fig.6. Because of variable wire gauge, each configuration has different cross-sectional area and resistance thereby consuming power accordingly. The diameter also affects the number of turns and the total length of wire which results in variable magnetic moment generation, variable generated torque at certain applied voltages. According to requirements, the required generated torque is not only main objective of compact magnetorquer but also the power consumption which should be as low as possible in addition to being low cost and light weight. The design parameters of Compact coil magnetorquer are shown in table 2.

Table 2

Compact coil magnetorquer design parameters

Parameter	Values
Average length of single turn	340 mm
Total length of Coil	65,200 mm
External turn side	90mm
Internal turn side	80mm
Cross sectional area of wire	$1.02 \times 10^{-7} \text{ m}^2$
Area occupied by all turns	1.38 m^2
Resistance per meter	168.9m Ω
Single coil resistance	11.01 Ω
Magnetic moment by coil	0.4152 Am ²
Max power consumption	0.9 Watt
Working voltage	32V-10V

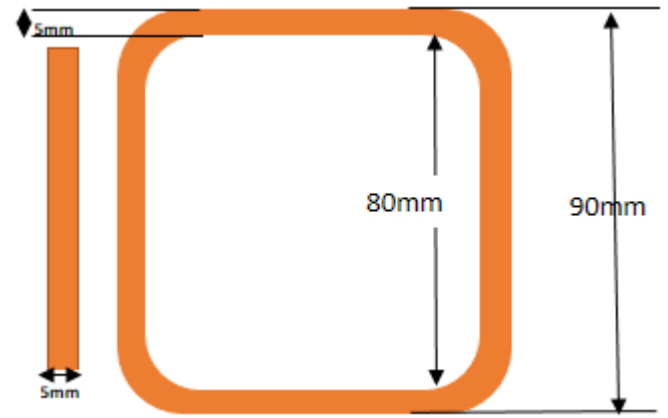


Fig.6 Cross-sectional view and dimensions of compact magnetorquer

For the analysis, we have plotted generated torque (in Nm), T/P (in Nm/W), power (in Watt) consumption and current (Amp). The symmetrical analysis of generated torque, torque to power ratio and thermal effects is plotted in Fig.7 for certain fixed wire gauge and variable applied voltage. The comparison has also been performed with the commercial available compact magnetorquer. The relation between applied voltage and torque to power ratio and temperature change of both designs is plotted in fig.7. The torque to power ratio decreases and temperature of the panel increases by increasing the applied voltage. This is so because of larger power consumption at higher applied voltages. Further comparison of both designs in Fig.7 represents that we achieve better torque to power ratio and temperature gradient as compared to the commercially available design.

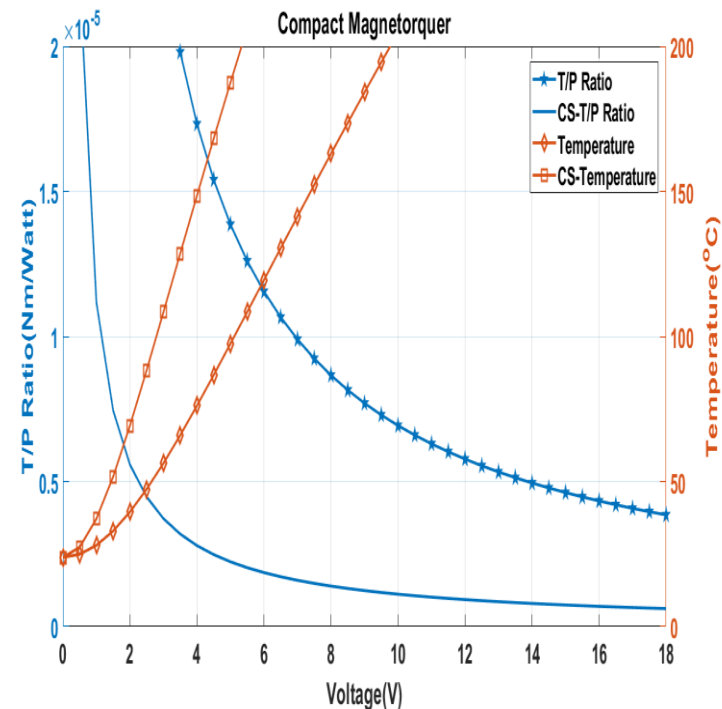


Fig.7 Internal side length Vs Torque, Power and current for compact magnetorquer

C. Cylindrical Magnetorquer

The cylindrical magnetic rod is the best available magnetorquer for the generation of higher torques and consequently better attitude controls. The magnetic rod is also designed which completely fits in the dimensions of a CubeSat. The magnetorquer rod design has been optimized by using optimum parameters including the length of rod, core radius, and radius for turns for selected wire gauges.

The detailed analysis of magnetorquer rod has been performed by changing the applied voltage, core radius, core length against the generated torque, power consumption, obtained torque to the power ratio, the magnetic field to the power ratio. The comparison has also been performed with the commercially available cylindrical magnetorquer with w.r.t. functional performance and thermal constraints. The analysis for our design is performed for different gauges wire (27-29). The optimum wire gauge for design is selected based upon above specified parameters. The wires of different wire diameter have different cross-sectional areas which effects the design parameters because it changes the total number of turns. The cross sectional view of the cylindrical magnetorquer is shown in Fig.8

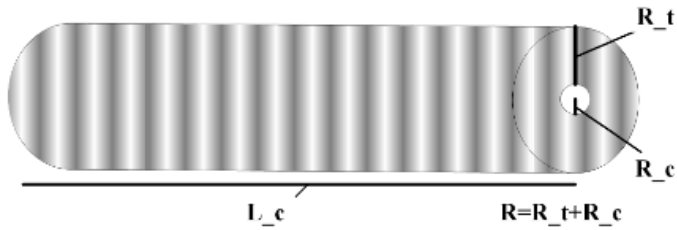


Fig.8 Cylindrical magnetorquer

According to the requirements, the generated torque is not only main objective of magnetorquer rod but also the lower power consumption in addition to low cost and light weight. The design parameters for the cylindrical Magnetorquer are shown in table 1.

Table 1
Magnetorquer rod design parameters

Parameter	Values
length of wire	48.9m
Length	75mm
Diameter	10mm
Cross sectional area of wire	0.065m ²
Area occupied by coil	0.0612m ²
Resistance per meter	268.5mΩ
Single coil resistance	13.14 Ω
Magnetic moment by coil	2.7 Am ²
Max power consumption	0.82 Watt
Working voltage	2V-10V

For the analysis, we have plotted generated torque (in Nm), T/P (in Nm/W), power (in Watt) consumption and current (Amp). It is evident from Fig.9 that by increasing the applied voltage,

the generated torque, and the torque to the power ratio decreases. Therefore, to conclude, it is recommended to operate the cylindrical magnetorquer at lower operating voltages so as to maximize the functional parameters.

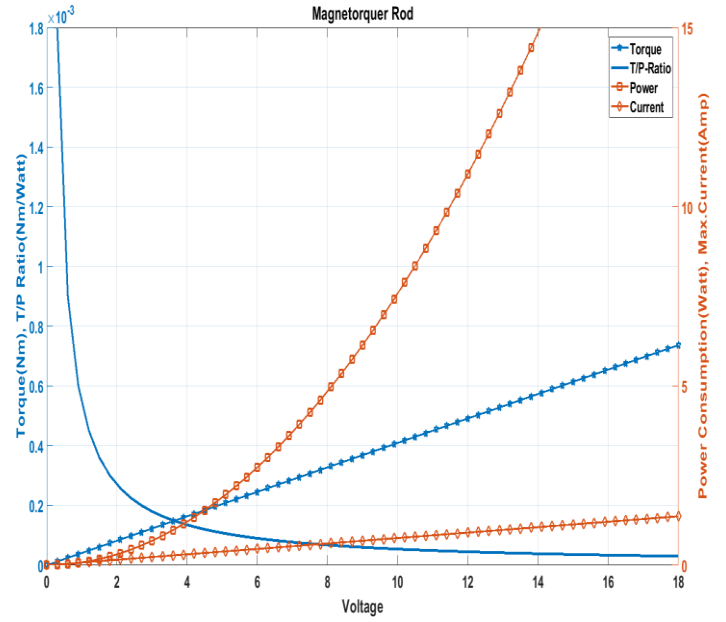


Fig.9 Voltage Vs T/P Ratio, Torque, Power and current for cylindrical magnetorquer

Fig.10 shows the relation between applied voltage and torque, torque to power ratio and the temperature rise with changing voltage. It suggest that low voltage is more suitable for high torque to power ratio and low temperature of magnetorquer.

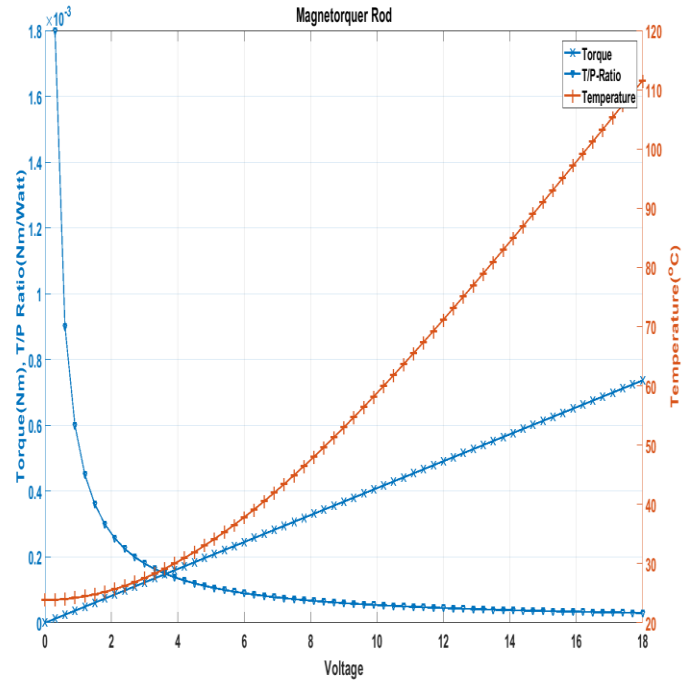


Fig.10 Voltage Vs Torque, T/P Ratio and temperature for cylindrical magnetorquer

III. COMPARISON ALL DESIGNS

The comparison of printed, compact and cylindrical magnetorquers has been performed in terms of generated torque, power consumed and applied voltage. It is concluded from the previous discussion that the torque and power consumption increases by increasing the applied voltage. The torque generated by the magnetorquer rod is greater than the compact and printed options but its power consumption is lower than compact coil and greater than printed coil. The maximum power is consumed by compact magnetorquer while its generated torque is greater than that of printed magnetorquer but smaller than magnetorquer rod. Printed generated low torque while consuming lower power than other two coils as shown in Fig.11.

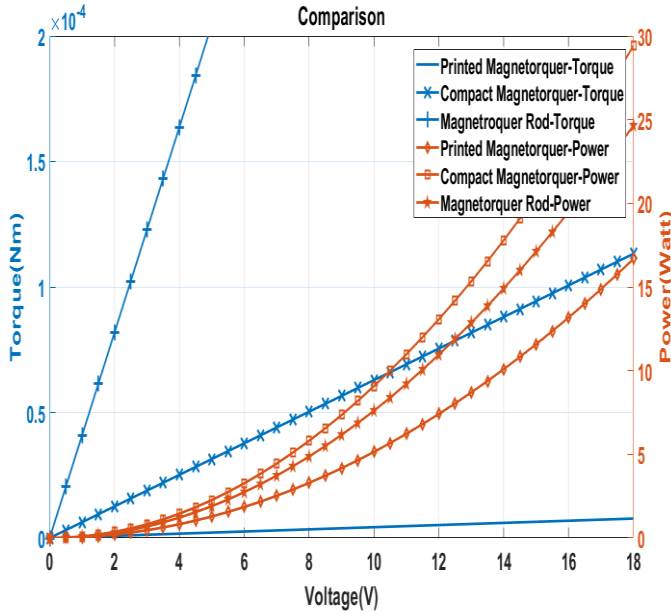


Fig.11 Comparison of printed, compact and cylindrical magnetorquers

It is evident from the above figure that the generated torque of magnetorquer rod is highest of the other coils.

IV. THERMAL ANALYSIS AND COMPARISON

The subsystems of a spacecraft can work in specified limit of temperature, they cannot work properly beyond this limit so we have to keep the temperature in limit. Here is the thermal analysis and comparison of all the magnetorquers to validate of our design. The thermal balance equation is used to find the temperature by varying different parameters [10].

The thermal analysis has been performed for all the three configurations by changing the applied voltage. It can be noticed from the plots of Fig.12 that the compact magnetorquer produces highest temperature rise as compared to the printed magnetorquer and magnetorquer rod whereas the printed coil consumes less power thereby dissipates less heat.

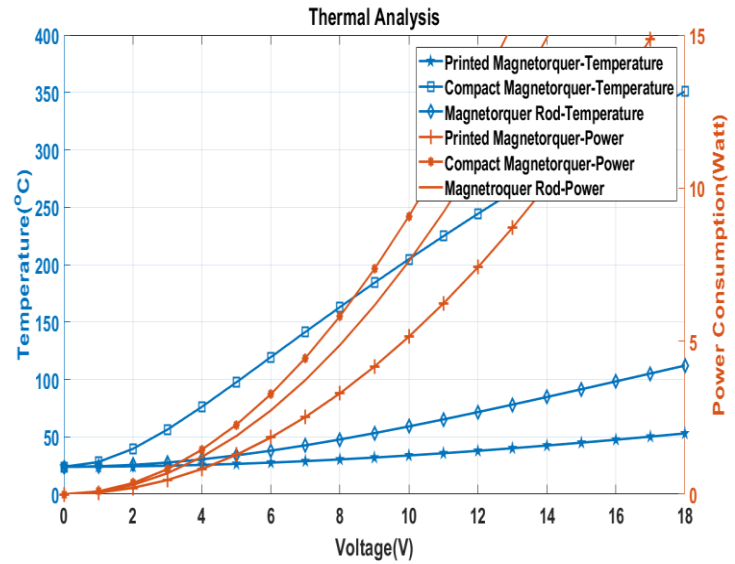


Fig.12 Thermal analysis of printed, compact and cylindrical magnetorquers

V. CONCLUSION

The presented design of compact, printed and cylindrical magnetorquers is fully compliant with the CubeSat panels and can be used based on mission specific needs. The analysis optimizes the key design features including generated torque, torque to power ratio, working voltages and thermal analysis for the selected coils. The presented design has been compared with the commercially available designs and the results have been plotted.

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